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INVESTIGATIONS WITH SATELLITE DATA
-TEMPERATURE RETRIEVALS-

BY
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TECHNICAL REPORT

by

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Introduction

It can be shown that there is no unique solution (e. g. Fritz, 1969) to the problem of atmospheric temperature retrievals from satellite radiance measurements. The problem which does remain is to find the "best" solution from the infinite set that exists.

For this purpose there is some merit in beginning with simulated "data" instead of real data, because one of the major difficulties with real data is that the true answer is not precisely known; real data contain various errors and uncertainties themselves. By contrast, for simulated "data", the true answer is known. And, further, all physical quantities which enter into the problem can also be simulated without error, a fact which is never true about the real atmosphere.

Because of these attributes, the processes used to retrieve the atmospheric vertical temperature distribution can be studied with simulated "data". And that process which produces temperatures closest to the known true temperatures can be judged to be the best from among those processes tried.

Almost all retrieval methods involve the multiplication of the measured radiances by some numbers. In particular, linear methods usually involve the search for a set of coefficients, F(k,j), such that

$$\Delta B(k) = \sum_j F(k,j) \cdot \Delta R(j)$$

will achieve the "best" solution. See Appendix (A). B(k) = Planck function at the pressure level, k, at a reference frequency, usually taken at 700 cm^{-1}, when the 15 μm CO_2 band is used in the satellite measurements.

R(j) is a radiance at the frequency, j.

The subscripts denote the following:

"g" = a guess (or initial estimate)

m = the measured value

r = the retrieved value.

Because B(k) depends only on the temperature, T(k), it is easy to compute T(k) from the inverse of the Planck function, once B(k) is known.

Two linear methods, the "minimum information" method and the regression method have been used operationally. The regression method defines the "best" coefficients, F(k,j) as the set which produces the smallest temperature error, in a least square sense, in a set of radiosonde data selected from a wide area during some time interval before the current satellite data are obtained at a particular place. A similar objective, but with additional assumptions, to make the problem more tractable, is employed in the minimum information method. In view of these limitations should one expect that the set of coefficients will produce the "best" temperature retrieval at a particular time and place? A recent paper (Fritz, 1976, see Appendix A) suggests that better results can be obtained. This is achieved by using the most recent radiosondes available and modifying the coefficients F(k,j) to a new set, G(k,j) so that retrieved temperatures agree exactly with one radiosonde temperature profile. Thus, instead of trying to "beat" or even match the radiosondes, we "join" the radiosondes and use the satellite radiances to improve temperature determination between the radiosonde stations and also in time until the next radiosonde launch times. This final report expands on a previous report which is included here as Appendix A. Appendix A, which has been submitted to the Journal of Applied Meteorology (JAM), summarizes the results obtained from simulated "soundings" for "stations" between Omaha, Nebraska and Springfield, Illinois. In this final report,

additional results are discussed; it also includes some findings obtained after the earlier report was submitted to the JAM.

Data Used

To investigate the effect of the coefficients two sets of "data" were used. One set depended on ship temperature soundings in the GATE project. Another depended on temperatures between Omaha, Nebraska, and Springfield, Illinois. The Omaha profile (which served as the "guess" profile in the retrieval method) and the Springfield temperature profile are shown in Fig. 1.

Effect of Noise Parameter on Minimum-Information Retrievals

With the Omaha temperatures as an aid, and with the transmittances, and their corrections for temperature supplied by Dr. M. Weinreb (NESS/NOAA), the coefficients F(k,j) used in the minimum information method, were computed. The F(k,j) depend on the noise parameter, σ_N included in the retrieval (See Appendix A eq. 4).

Fig. 2 is a plot of the average temperature error, ΔT averaged over the various layers indicated, as a function of the σ_N for the station pair, Omaha (first guess) and Springfield, Illinois (retrieval). In deriving Fig. 2, the "measured" radiances contained no errors. We note that as σ_N approached zero, ΔT often became large. Thus for the layer 1000-800 mbs, ΔT = 10.4K; for the layer 800-600 mb, ΔT was -13.3K. And, for σ_N large, ΔT approaches the difference between the first guess temperature and the true temperature, because F(k,j) and $\Delta B(k)$ approach zero (see eq. 4 in Appendix A). At least for the one sounding (Springfield) if we accept the interpolations in Fig. 2, there was no single value of σ_N which would make $\Delta T = 0$ for all layers. For the layer 1000-800 mbs apparently

σ_N = 1.0 would have made $\Delta T = 0$, for the layer 600-400 mbs, $\sigma_N \simeq 0.15$ would have been best, while for the other layers there may not have been any value of σ_N which would have made $\Delta T = 0$. Thus since F(k,j) is sensitive to the value of σ_N, it seems evident that it would be impossible to find a set of F(k,j) which could make $\Delta T = 0$ for all layers. In view of this defect, it seems advisable to seek a set of coefficients, G(k,j) which would make $\Delta T = 0$, at least at Springfield. Apparently such a set of G(k,j) cannot be obtained by adjusting σ_N, and possibly not even by adjusting other parameters in the minimum information method.

Vertical Distribution of Coefficients

Since we employed the six 15 μm CO_2 channels used in the VTPR instruments, at each pressure level, k, in the atmosphere, there are six coefficients, one from each spectral interval, j; i.e., at each pressure level there are six values of F(k.j).

There are an infinite number of ways in which the F(k,j) can be modified to make $\Delta T = 0$ at Springfield. A few were tried so far in this study.

These included the following methods: (see Appendix B, for the equations for the various methods.)

(1) Change one of the F(k,j) so that $\Delta T = 0$. To do this the largest (in absolute value) of the six F(k,j) at each level was changed.

(2) Change all the F(k,j) by multiplying them by a constant; thus

$$G(k,j) = C(k) \cdot F(k,j)$$

This method used in Appendix A.

Methods 3 and 4.

Make the sum of G(k,j) = 1.0. This was done in two ways.

(3) Change the two values of F(k,j) for which the absolute values of F(k,j) were the largest. As in Methods (1) and (2) above, certain instabilities occur in the resulting G(k,j). Therefore Method (4) was devised.

(4) Change the highest absolute value of F(k,j) and also the one for which $\Delta R(j)$ was the furthest away from $\Delta R(j_{max})$; that is,

$$|\Delta R(j_{max}) - \Delta R(j)| = \text{maximum}$$

This makes the G(k,j) stable with k.

The vertical distribution of F(k,j) (minimum-information) and G(k,j) (adjusted) are shown for several spectral channels and for several methods in Fig. 3

The coefficients, F(k,j) for three spectral channels are plotted in Fig. 3(a) against the vertical coordinate, k. (The other channels are not shown to avoid complicating the diagram). These are the coefficients obtained in the minimum-information retrieval method, when the temperatures at Omaha are used as a first guess in order to apply temperature corrections to the transmittances; the vertical variation of the transmittances, to a large extent, determine the coefficients.

For channel 6, $\nu = 747.6\ \text{cm}^{-1}$, the largest coefficients are found near the ground. Thus at p = 1000 mbs, F(100,6) = 4.9. We shall find below that this is a large value, and is doubtless responsible for the large temperature errors produced in the minimum-information method. The other channels shown have little influence near the ground: however, channel 5 (not shown) has an influence almost as great as channel 6.

Near the 150 mb level, channel 3, $\nu = 695.3\ cm^{-1}$, has the greatest influence of those channels shown; and finally, channel 1, $\nu = 668.5\ cm^{-1}$ has the greatest influence near the top of the atmosphere, near the 2 mb level.

By comparison, the coefficients G(k,j) are shown in Figs. 3(b), 3(c) and 3(d) for several other retrieval methods.

Fig. 3(b) shows the results for channel 6. In Fig. 3(b) curve 3 is the same as F(k,6) in Fig. 3(a). This is the minimum-information method curve. The coefficients G(k,j) derived from 3 of the adjustment methods are also shown in Fig. 3(b). The significant result is that in the lower atmosphere, near p = 1000, the adjustment coefficients are much smaller than F(k,j). The values of G(100,6) vary from about 3 down to about 0.5, whereas F(100,6) is 4.9. This indicates that in order to obtain small temperature errors below the 900 level, the minimum-information coefficients must be substantially reduced in the lower atmospheres.

Fig. 3(b) also shows the instability in the G(k,j) introduced when the denominator in the adjustment computations get too small (see Appendix B). Thus for curve number 4, near the 270 mb level, the coefficients, oscillate rapidly between about -3 and +8.1. However this oscillation is eliminated in Method 4 as shown in curve B, for which $\sum_j G(k,j) = 1$. Fig. 3(c) shows similar results for channel 3, $\nu = 695.3\ cm^{-1}$. Here curve (C) is the same as F(k,j) in Fig. 3(a) for channel 3. Fig. 3(c) shows how unstable some of the adjustment methods can become. By contrast, curve B, which shows the G(k,j) for Method 4, shows how stable the coefficients are. Still the relatively small differences from the minimum-information coefficients are required to reduce the temperature error to zero at Springfield.

Finally Fig. 3(d) shows similar curves for channel 1, $\nu = 668.5\ cm^{-1}$. Here, of course, the major changes occur near the top of the atmosphere. Curve A, adjustment method 3, gave poorer results; the coefficients are large, because the denominator in the calculation of G(k,j) are too small in Method 3 for that part of the atmosphere. Again Method 4, yielded stable coefficients and gave relatively small errors (see Figs. 4 and 5).

Making $\sum_j G(k,j) = 1.0$ can be justified somewhat by the following reasoning:

Consider an isothermal atmosphere; then

$$R_t(j) = \sum_k B_t(k,j)\Delta\tau(k,j) = B_t(k,j)\sum_k \Delta\tau(k,j) = B_t(k,j) = B_t(T_t,j)$$

since $\sum_k \Delta\tau(k,j) = 1$, and T_t is independent of height (subscript "t" = true).

If we select also an isothermal first guess profile, $B_g(k)$, then, similarly, $R_g(j) = B_g(T_g,j)$, and

$$\Delta R(j) = R_t(j) - R_g(j) = B_t(T_t,j) - B_g(T_g,j) \approx B_t(T_t,700) - B_g(T_g,700)$$

$$= \text{constant}$$

Therefore $\Delta R(j)$ is nearly constant and nearly independent of frequency, j.

Moreover, $B_t(k,700) - B_g(k,700) = \Delta B_t(k,700) = \Sigma G(k,j)\cdot\Delta R(j)$

Therefore $\Delta R(j) = \Delta R(j)\ \Sigma G(k,j)$

and $\Sigma G(k,j) = 1$.

Similarly, $\Sigma G(k,j)$ would doubtless also equal about 1.0 if the first-guess profile differed at all levels by a constant temperature difference, say, 3K, from the true temperature for a realistic non-isothermal atmosphere. The reasoning would be similar to that for an isothermal atmosphere; but the answer would not be as accurate because the Planck Function, $B(k,j)$ is not exactly linear with temperature. If the first-guess temperature profile differs in arbitrary ways from the true profile, the assumption of $\Sigma G(k,j) = 1$ might be less justified.

It should be emphasized that for all these methods, $\Delta T = 0$, exactly, at Springfield. However the application of the coefficients, at "stations" between Omaha and Springfield, did not yield identical results because the $\Delta R(j)$ were, of course, different for the intermediate stations from their values for Springfield. The results are given in Table 1.

Table 1 shows that the average absolute error of the "adjustment" retrieval temperatures averaged over 200 mb layers is smaller than the minimum-information retrievals at all levels except the 200-5 mb stratospheric layer, where for most methods the error was small anyway. Most striking, however, is the improvement of all four adjustment methods, over the minimum-information method, in the layer from 1000-800 mbs. Whereas, the minimum-information method makes essentially no improvement over the first-guess error of 3K, the adjustment method Nos. (2) and (3) reduce the error to less than 0.5K. Method (2) involves division by $[B_r(k) - B_g(k)] = \Delta B_{rg}$. This quantity approaches zero when the retrieved temperature is approximately equal to the first guess temperature. Under those conditions, ΔT_r may be large and oscillate in sign. Yet as can be seen from Table 1, ΔT averaged over 200 mb layers was small. This is a result of the fact that when $B_r(k) \approx B_g(k)$ the sign of $(B_r - B_g)$ itself

TABLE 1. Average Absolute Temp Error (^{o}K)

Δp (mb)	FG-True	Min Info	Adjustment Method 1	(Best) 2	3	4
1000-800	3.0	2.9	[1.0]	0.3	0.4	0.6
800-600	7.4	2.3	[1.6]	1.2	1.5	1.6
600-400	7.1	1.6	[1.9]	1.0	1.0	1.0
400-200	4.0	3.8	[1.8]	1.2	2.0	1.3
200-5	4.6	0.1	[0.1]	0.2	0.8	0.2

<u>Adjustment Method</u> (see p. 4, 5)

*[(1), $G(k,j) = F(k,j)$; $G(k,j_{max}) = C'(k) \cdot F(k,j_{max})$]

(2), $G(k,j) = C(k) \cdot F(k,j)$ for all j

(3), $\Sigma G(k,j) = 1.0$; $G(k,j) = F(k,j)$; $G(k,j_{max})$; $G(k,j_{max-1})$

(4), $\Sigma G(k,j) = 1.0$; $G(k,j) = F(k,j)$, $G(k,j_{max})$; $G(k,j)$

$$|\Delta R(j_{max}) - \Delta R(j')| = \text{maximum}$$

*[for Method No. 1

(Omaha + 90 km) was used for the adjustment instead of Springfield, Illinois. A test showed that even when this station was used with all F(k,j) changed, the result was more similar to the results shown above for Method (2). Also, it should be noted that in that early test, Omaha, the first guess station, was inadvertently made super adiabatic from the surface to 700 mb; the temperature at 700 mbs was about 9K colder than in the later tests.]

oscillates in sign with height about the critical height. Thus in Fig. 1 at about 275 mbs, $B_r(k) = B_g(k)$; but just above that level ΔB_{rg} is negative and just below 275 mbs ΔB_{rg} is positive. Therefore, if one averages over the layer from 400-200 mbs, $\overline{\Delta T}$ appears to be quite stable. However for individual pressure levels, which should not in any case be used for temperature retrievals, ΔT can be large. For example,

Temperature Error (^{o}K)

	Station				
P(mb)	Omaha +90 km	+180	+270	+360	+450
285	+3.5	+2.4	+2.7	+3.7	1.0
271	+25.1	+1.9	+4.6	+22.0	+5.2
258	-11.0	+2.6	+2.9	-8.4	-1.8
245	-5.4	+2.5	+3.7	-3.9	-1.0

At 271 mbs, $\Delta T = 25.1$ at station Omaha + 90 km, and 22.0 at station Omaha + 360 km. Clearly near the 271 mb level, the retrievals are sensitive to the radiances because the $G(k,j)$ have large absolute values.

To overcome such large ΔT oscillation at particular pressure levels, we may average the values of $G(k,j)$ over a few levels. But it seemed to be preferable to use Method (4) mentioned under Table 1. With that method we get more stable values, as for example

Temperature Error (^{o}K)

	Station				
P(mb)	Omaha +90 km	+180	+270	+360	+450
285	-1.1	2.8	2.5	0.0	0.7
271	-1.0	2.8	3.0	0.1	0.7
258	-0.9	2.7	3.4	0.1	0.6
245	-1.0	2.7	3.8	0.2	0.7

The GATE Experiment

Before the Omaha-Springfield experiment was run, an experiment was run involving soundings from the Canadian Ship QUADRA, located at about 9.3N, 22W, one of the ships in the GARP Atlantic Tropical Experiment (GATE). Atmospheric temperature soundings were available for 1800Z on eight days between the period July 5, 1974 and August 8, 1974. For the eight days, data for one day was used as the first guess, and data for the next available date were used as the truth [actually the order was inadvertently reversed so that, e. g., data for July 8 were used as the first guess for retrieval of July 5 data; the computation was not changed, because for the purpose of this study, the order does not make any difference.] In this early experiment, comparison was again made between the retrievals for the minimum-information method, and the adjustment method. For the adjustment method the coefficients F(k,j) were modified by two of the different ways discussed above; namely, Methods (1) and (2). The results are shown in Table 2.

TABLE 2
Average Absolute Temperature Error (^{o}K)
for GATE Ship Quadra

	Method		Adjustment	
ΔP(mbs)	FG-True	Min-Info	1	2
1000-800	1.8	3.3	0.5	0.5
800-600	1.3	2.2	0.8	0.7
600-400	0.4	0.4	0.6	0.7
400-200	0.6	0.9	1.2	0.8
200-5	2.8	0.6	0.4	0.4

FG = First Guess
Min-Info = Minimum-information method

In Table 2, again, the minimum-information method yields poorer results than even the first guess in the lower layers, below 600 mbs. But the adjustment method improves over the first guess. (It should be noted, however, that the ship's observations might have been in error; on some days the average temperature in the layer 1000-800 mbs, differed from the adjacent day's temperature by over 3.5K; this seems like a rather large change in the tropics. Since the radiances in this study were simulated, any measurement errors on the ship would not affect the results. In a real case, however, ship temperature measurement errors would lead to inconsistencies with satellite observed radiances, and apparent "errors" would show up in retrieval comparisons with radiosonde temperature measurements).

At intermediate levels, between 600 mbs and 200 mbs, the first guess error (i.e., the observed variation from day to day) is so small, namely about 0.5K, that none of the methods can improve on the first guess. In this pressure interval, the minimum-information method did as well, or even better than the adjustment method.

For the layer from 200-5 mbs, the first guess error was rather large. This was caused by a rather poor add-on of temperature profile for the high layers above the radiosonde level. In this layer the retrievals by all methods were rather good. This is a bit surprising, perhaps, because this layer contained the tropopause, which was located at about the 100 mb level. Usually, the minimum-information method yields large errors near the tropopause. Perhaps, in this study, the layer 200-5 mbs is large enough to eliminate errors which appear in thin layers, or at particular pressure levels.

Results for Other Layer Thicknesses (Omaha-Springfield)

There is considerable discussion in the literature regarding the vertical resolution, or vertical resolving power, of the temperature retrievals from satellite data [e.g., Conrath, 1972; Thompson, et al., 1976]. Everyone concludes that there is a trade-off between the vertical thickness over which the retrievals are averaged, and the error of the temperature retrievals. In this study the temperature averaged in the vertical over various pressure layer intervals was computed. The results are shown in Fig. 4. The figure shows the average absolute temperature error averaged over the five "stations" between Omaha and Springfield, for various layers above 1000 mbs, i. e., the ordinate 900 mbs means the layer from 1000-900 mbs, the ordinate 800 mbs means the layer from 1000-800 mbs, etc. Figure 4 shows that for layers thinner than 1000-500 mbs, the minimum-information results were substantially poorer than for any of the adjustment methods. Actually for the layer from 1000-900 mbs, the minimum-information retrievals were much poorer than the first guess error; for, whereas the first guess temperature error was about 1.5K, the minimum-information retrieval was more than 4K for that layer. Even for the layer 1000-800 mbs (as already noted) the minimum-information retrievals did not improve over the first guess. It is not until the thickness reaches 1000-500 mbs that the minimum-information retrieval errors are approximately as small as the adjustment method retrievals. This suggests that in the lower atmosphere, the vertical resolution, with the minimum-information method, for average absolute temperature errors of about 1K, is about 500 mbs.

However, Fig. 4 shows that with adjusted coefficients, the temperature error is less than 1K even for layers as thin as the 1000-900 mb layer.

From the theoretical results which estimate the vertical resolution on the basis of the transmittances and the "weighting functions" (Conrath, 1972), it is not likely that the good results for the adjustment method depends on any inherent resolving power in the satellite radiances. Rather, the adjustment method is doubtless taking advantage of the similarity in the structure of the vertical temperature profiles at the interpolated "stations" and at the nearby radiosonde stations.

For the average absolute temperature error for the layers thicker than 1000-300 mbs, the results seem more erratic. We note that Method 3 ($\Sigma G = 1$) shows the poorest results for the layer 1000-100 mbs. This happened because the coefficients $G(k,j)$ became very large in the layers involving channels 2 and 3. For those channels, the ΔR were respectively -10.33 and -10.56; the difference between these is the small value 0.228. Since this small number, 0.23, appears in the denominator at those levels, k, where $F(k,j)$ are maximum for channel 2 and next to the maximum for channel 3, the coefficient $G(k,j)$ will be large in the height intervals where channel 2 and channel 3 dominate. When those large coefficients, derived from the Omaha-Springfield pair, are then applied to other stations, the results are likely to show large errors. Moreover in this method of finding $G(k,j)$ unlike Method 2, for which $G(k,j) = C(k) \cdot F(k,j)$, the large values of $G(k,j)$ will persist over a deep layer as long as $F(k,j)$ is the largest of the six values at any level, k. Thus, for example, in the "Omaha + 90 km" sounding, the temperature error was between -4.9K and -11.75K at all levels between 233 mbs and 141 mbs. Such large temperatures of the same sign for such a deep layer will produce large temperature errors even if averaged over a deep layer, and will also adversely affect the height errors as we shall see presently. By contrast, large temperature

errors, of even 20K, in Method 2, [G(k,j) = C(k) F(K,j)], do not produce poor results over layers, because the sign of the error for adjacent values of "k" generally oscillate in sign.

The Height Error for Various Pressure Levels

In this study, the height was assumed known at the 850 mb level, where the height was taken to be 1330 m. The height Z(k) for various pressure surfaces, k, was computed from the 850 mb height and the retrieved temperature structure from the formula

$$Z(k) = Z(k-1) - \left(\frac{R^*}{g}\right) \frac{[T(k) + T(k-1)]}{2} [\ln p(k) - \ln p(k-1)]$$

$$\frac{R^*}{g} = 29.287$$

The results, in Fig. 5, show that Method 4, [ΣG(k,j) = 1, MOD], and Method 2 [G(k,j) = C(k)·F(k,j)] gave the best results. At all pressure levels up to 10 mbs, the average absolute height error did not exceed 20 m; in general, the second of these two methods gave somewhat better results than the first method. The other methods illustrated in Fig. 5, show that the minimum-information method was poorest at 500 mbs although all methods improved substantially over the first-guess height difference from the true heights. At the 100 mb level, Method 3, [ΣG(k,j) = 1] (two largest coefficients changed) gave the poorest, results, and even did not improve over the first guess height error. This resulted from the fact that, as stated earlier, large temperature errors, of the same sign persisted over relatively thick layers.

From the results in Figs. 4 and 5 and from Table 1, it appears that Methods (2) and (4) gave the best results; and if, for some reason, it is

necessary to avoid large oscillations in the temperature for individual pressure levels, Method (4) would be the one recommended.

Values of $F(k,j)$ $\Delta R(j)$ and $B(k,700)$ - Their Relationship
Linear Methods

As stated earlier, linear methods generally solve the satellite temperature retrieval problem by solving for

$$B_r(k) = B_g(k) + \Delta B_r(k)$$

$$\Delta B_r = \sum_j F(k,j)\cdot\Delta R(j)$$

$$\Delta R(j) = R_m(j) - R_g(j)$$

In the minimum-information method, an attempt is often made to make $B_g(k)$ as close as possible to the true value. This can be done, for example, by selecting NMC's latest 12 hour forecast at the place where the satellite measurements are being made. This would also have the tendency to make $\Delta R(j)$ small, because $R_g(j)$ would approximate $R_m(j)$. In particular if all $B_g(k) = B_t(k)$(although this would not be known to the experimenter), $\Delta R(j) \simeq 0$ and it would not make any difference what values $F(k,j)$ had. [Even if $B_g(k) \equiv B_t(k)$, ΔR would not equal zero exactly, because, the $\tau(k,j)$ used to compute $R_g(j)$ would not be exactly the same as the value in the real atmosphere; the real τ's are the only ones which the satellite experiences when it measures $R_m(j)$]. In practice, of course $B_g(k)$ does not equal $B_t(k)$, and $\Delta R(j) \neq 0$. Therefore, the values selected for $F(k,j)$ become important; the set of $F(k,j)$ selected will strongly influence the resulting values of $B_r(k)$ and therefore of $T_r(k)$. Since a value of $\Delta R(j) = 0$ would most likely result from a value of $B_g(k) \simeq B_t(k)$, the retrieval error would tend to be smaller, the smaller $\Delta R(j)$ is.

However in the adjustment method in which, for example, $G(k,j) = C(k) \cdot F(k,j)$, the retrieval error does not necessarily get smaller as ΔR gets smaller. Take, for example the results for the Omaha-Springfield experiment reported above. The retrieval error is exactly zero in two instances; once when ΔR is a maximum, i. e., at Springfield, and again when $\Delta R = 0$, and also $(B_g - B_t) = 0$, i. e., at Omaha. The error is zero at Springfield only because the $G(k,j)$ have been so selected, so that for the given values of $B_g(k)$ and therefore of $R_g(j)$ and of $\Delta R(j)$, (all of which are not optimum from the minimum-information method point of view), $B_r(k) = B_t(k)$. Now as we proceed from Springfield towards Omaha, $\Delta R(j)$ generally* becomes smaller and $B_g(k)$ approaches $B_t(k)$ for the particular "station". Still, the adjustment method derives better retrievals, probably because the influence of the $G(k,j)$ is dominant over the $\Delta R(j)$ and $B_g(k)$. However, when we arrive at the station "Omaha + 90 km" the minimum-information retrieval is better than the "adjustment" method retrieval for deep layers, as indicated by the 510 mb height error (in Table 3 of the Appendix A). At the "Omaha + 90 km" station the height error for the minimum-information method is 14 m; for the adjustment method it is 23 m. At all other stations further from Omaha, the height error is larger for the minimum-information method.

In summary there are two main factors which affect the retrieval accuracy with simulated data; namely B_g and ΔB_r. And ΔB_r in turn depends

*Table (3) shows the values of $\Delta R(j)$ and of $N(j)$ for each station between Omaha and Springfield. Although the $|\Delta R(j)|$ generally decrease from Springfield to Omaha, they do not do so monotomically; this is doubtless due in part to the random nature of the noise added to the radiances, and partly to the fact that the gradient of temperature was toward Omaha (low temp) in midtroposphere, but was reversed above the 200 mb level. The radiances are affected by temperatures over a deep layer.

TABLE 3.

$\Delta R(j) = (R_m - R_g)$

Chan. No.	Springfield Omaha		Omaha + 90 km	+180	+270	+360	+450
			Station				
1	-6.53		-1.30	1.98	-2.57	-6.23	-5.67
2	-10.33		-1.69	-3.90	-4.21	-8.64	-8.27
3	-10.56		-2.18	-4.22	-4.36	-9.18	-8.86
4	-1.63		-0.46	-0.10	-0.04	-1.74	-0.90
5	2.37		-0.79	2.29	2.97	1.88	2.61
6	3.29		2.36	3.22	3.16	3.23	3.68
			Radiance Noise				
	Springfield						
1	.11		-.09	.43	-.15	-.73	-.16
2	-.04		.22	-.08	-.37	-.08	.31
3	.18		-.08	.16	.12	-.06	.26
4	.21		-.10	.41	-.06	-.17	.49
5	.05		-.28	-.04	.02	-.47	.13
6	-.17		.21	.47	-.04	-.10	.28
			Radiances				
	FG Omaha	Spring-field					
1	71.5	65.2	70.4	69.8	69.2	65.5	66.1
2	66.8	56.4	65.1	62.9	62.5	58.1	58.5
3	63.1	52.5	60.9	58.9	58.7	53.9	54.2
4	66.6	65.0	66.2	66.7	66.7	64.9	65.7
5	89.5	91.9	90.3	91.8	92.5	91.4	92.1
6	110.2	113.5	112.5	113.4	113.3	113.4	113.8

on F(k,j) and $\Delta R(j)$. Moreover $\Delta R(j)$ depends on R_g and therefore also on B_g. The F(k,j) depend on $\frac{\partial \tau(k,j)}{\partial x}$, where x is an atmospheric pressure parameter. And since the τ's are temperature dependent, and in practice are adjusted with the first guess temperatures, even the F(k,j) also depend somewhat on B_g. Therefore B_g enters the problem in three ways in the minimum-information method. And since in the Omaha-Springfield set, the Omaha first guess is furthest from the true value at Springfield, the errors in the minimum-information method might be largest at Springfield when Omaha is used as the first guess.

However, in the adjustment method used in this report, the temperature error is forced to be zero at Springfield, just where the first-guess error is largest. And since the vertical temperature profile structure is probably more nearly like the Springfield profile for the "stations" nearest to Springfield, one might expect that the coefficients G(k,j) would have an opposing effect to the effect of B_g. Thus the computed temperatures retrieved from the adjustment method, at a particular "station" between Omaha and Springfield, would depend on the relative influence of $(B_g - B_t)$ at the station vs. the influence of the G(k,j) which have their maximum effect at Springfield (where Omaha is used as the first guess). In the test performed in this report, judging by the 510 mb height error comparisons in Table 3 of Appendix A, the influence of the G(k,j) seems to have dominated except at the station "Omaha + 90 km". Perhaps at that station the smallness of $(B_g - B_t)$ might have dominated. However, more tests will be needed before the arguments presented here can be accepted. Preliminary results, based on a reversal of the roles of Springfield and Omaha, raise some questions about the relative roles of $B_g(k)$ and G(k,j).

An indication of the composite influence of the various factors is shown in Fig. 6. This figure shows the temperature error for each station for layers 200 mbs thick, namely, 1000-800 mbs, 800-600 mbs, 600-400 mbs, and 400-200 mbs. The station numbers refer to the distance from Omaha, e. g., number 2 is 90 km from Omaha, number 3 is 180 km from Omaha, etc. Figure 6 shows that the temperature errors near stations 5 and 6 were always small for the adjustment method. This is undoubtedly the influence of the G(k,j) which had been selected, so that with Omaha as the first guess, the retrieval error would be zero at Springfield (90 km further from Omaha than station 6). The minimum-information method, almost always, gives a larger temperature error than the adjustment method especially at stations 5 and 6. As we approach Omaha, however the minimum-information method error becomes smaller, relative to the adjustment method. In fact, at station No. 2, in two layers, namely the layers 800-600 mbs and 400-200 mbs the minimum-information method error is somewhat smaller than the adjustment error. At station No. 2, the first guess error is smallest, $\Delta R(j)$ is smallest, and the influence of the F(k,j) and of the G(k,j) is reduced since they are multiplied by the $\Delta R(j)$ to yield $\Delta B_r(k)$.

Interestingly, the retrievals in both methods, yield either maxima or minima at station No. 4, midway between Omaha and Springfield. The precise reason for that behavior is not obvious. Doubtless it represents the interacting influence of the three factors, $B_g(k)$, $\Delta R(j)$ and F(k,j) or G(k,j) as the distance from Omaha increases.

Some Philosophical Questions

In the linear methods of retrievals the method often involves finding

$$B_r(k) = B_g(k) + \Delta B(k)$$

$$\Delta B(k) = B_r(k) - B_g(k) = \sum_j F(k,j)\; R(j) = \sum_j F(k,j)[R_m(k) - R_g(k)]$$

The basic idea is to select, in some way, the coefficients F(k,j), which when multiplied by the $\Delta R(j)$ will give the "best" value of $\Delta B_r(k)$. This value of $\Delta B_r(k)$ is then to be added to $B_g(k)$ so that $B_r(k)$ will be as close to the true value, $B_t(k)$, as possible.

However to a certain extent the coefficients F(k,j) are selected independently of $\Delta R(j)$. In the minimum-information method $F(k,j) = A^T[AA^T + \gamma I]^{-1}$ (see Appendix A) where

$$A(k,j) = \frac{d\tau(k,j)}{dx(k)}$$

$$\gamma = \left(\frac{\sigma_N}{\sigma_T}\right)^2 \quad \text{(see eq. 4 in Appendix A).}$$

"x" being a height parameter, usually some function of pressure, such as $p^{2/7}$. Since the τ's are temperature dependent, the A's are also temperature dependent; the A's therefore depend on the first guess temperatures, which are generally not equal to the true temperature. Moreover in the real case the A(k,j), even for a standard atmosphere, may have been computed from theoretical evaluation of the CO_2 15 µm spectrum and may not be strictly correct; (but, in the simulated procedures, this should not be a factor). In addition, the selection of the value of γ will strongly influence the value of the F(k,j). Normally, the "γ" is chosen to be compatible with

the values of the noise in the satellite instrument. But we found in this research that even if the noise is zero in the radiances, and we set $\gamma = 0$ the temperatures near 1000 mb level in the minimum-information retrievals contain very large errors, because the $F(k,j)$, with k corresponding to $p = 1000$ mb, have very large values, oscillating in sign with frequency, j.

One may ask then, what value of γ should be selected, when the noise in the radiances is zero? In this research a value of $\gamma = (0.25)^2/100$ yielded what seemed to be stable values of ΔT_r of about 3°K near the surface. Values of $\gamma = 0$ gave unrealistically large errors. And values of γ very large make the retrievals approach the first guess. These results were found when the radiances contained no error, and also when the radiances contained typical instrumental noise errors. Therefore, the value of γ seems to be somewhat arbitrary and is not linked closely to the instrumental noise, except possibly when the instrumental noise is very large. This also, therefore, implies that the coefficients, $F(k,j)$ are somewhat arbitrary and not necessarily optimum for a particular atmospheric situation. Therefore the method of adjustment proposed here, seems to have merit, from the philosophical point at least, since it adjusts the $F(k,j)$ to radiosonde temperatures near the times and place of the satellite measurements.

Some values of F(100,j) for the Omaha sounding as function of σ_N are shown in the following table:

F(100,j) (p = 1000 mbs)

σ_N	1	2	3	4	5	6
0	+.2444+01	+.2399+01	-.3757+01	+.1968+02	-.7772+02	+.7734+02
0.050, 5 x 0.025	+.1887+01	+.1106+01	-.1691+01	+.1299+02	-.5608+02	+.5735+02
0.50, 5 x 0.25	-.3996-01	-.5162+00	+.1333+01	-.2492+01	-.5643+00	+.4794+01
5.0, 5 x 2.5	-.1548-02	-.1087-01	-.1930-01	-.2968-01	+.1924+00	+.2624+00
Adjusted Value	+.3092-02	-.3994-01	+.1031+00	-.1928+00	-.4365-01	+.3708+00

The first value under column σ_N gives the value for Channel 1. Then the five noise values used for the other five channels are given. The values of σ_N are the numbers used in eq. 4 (Appendix A) and are not the values added to the computed true radiances. In this table the numbers +01, +02, -01, +00 refer to the exponent of 10; thus +.2444+01 means 2.444.

We note that the coefficient in all channels increase in absolute magnitude in all channels with decreasing σ_N, when p = 1000 mbs. And when the large coefficients are applied to the radiances, large errors in temperature are computed. Since it would be difficult to select the "best" set of F(100,j) the adjustment method which yields G(100,j) seems like a reasonable approach.

Hurricanes

It would be nice if something could be done to measure temperature changes which occur around tropical disturbances which develop into hurricanes. If

the temperature changes were large enough and could be eventually monitored from geostationary satellites perhaps forecasters would have a tool for forecasting hurricane development. However, since the central part of hurricanes, except for the eye, is always occupied by extensive cloud cover, infra-red measurements cannot be expected to indicate much about the temperature changes inside the cloudy area.

We therefore collected radiosonde temperatures for areas surrounding Hurricanes Camille (August 1969) and Celia (August 1970) in various stages of development. These data were plotted in several ways. For example at the 700 mb and 500 mb levels polar diagram charts were prepared which showed the temperature distribution at all azimuths and at distances from less than 200 km to about 1000 km from the storm center. In order to get sufficient coverage, the data were plotted for several days, on one chart, all relative to the storm centers. For Camille, this was done separately for the tropical disturbance stage and separately for the hurricane stage. In addition cross-sections were also plotted, in which the azimuth was the abscissa and standard pressure level was the ordinate. This was done for the distance ranging from 400 km to 800 km; this distance is well beyond most central overcast areas which generally do not exceed 300 km in radius.

The result indicated that temperature distributions about the storms varied by about 2-3^{o}K, which agrees with the findings of other investigators. There was a tendency for the western (forward) side of the hurricanes to be about 2^{o}K warmer than the eastern side. Moreover, in Hurricane Camille, the hurricane stage was about 2^{o}K warmer than the "disturbance" stage in the western part of the storm.

If these results are typical, and *if* the changes typically occur in sufficiently thick layers (at least 200 mb thick), so that it might

be possible to detect the changes from satellite radiance measurements, and if the retrieval process can detect changes of 2-3^{o}K in the presence of inevitable "noise" sources, the satellite data might be able to serve as a forecasting aid. To pursue this further, it will be necessary eventually to examine real satellite data over tropical disturbances and hurricanes together with airplane and other types of data.

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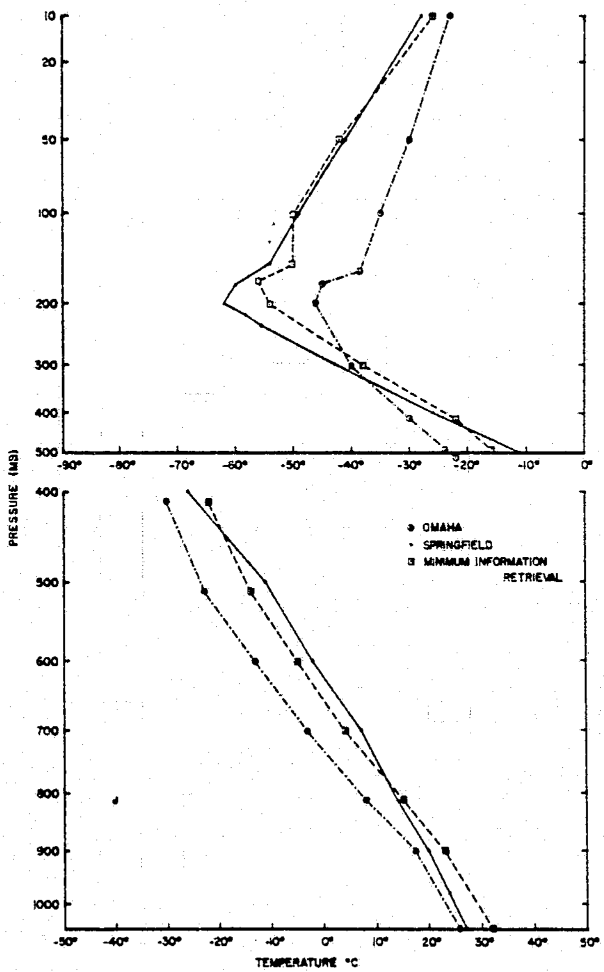

Fig. 1. Vertical temperature profiles. Omaha temperature profile was used as a "first guess". Springfield temperature profile was used as the "true" temperature, in order to compute the "measured" radiance, and to judge the retrieval error, at Springfield. The minimum-information retrieval profile was computed by using Omaha as the "first guess" and the simulated "measured" radiance at Springfield.

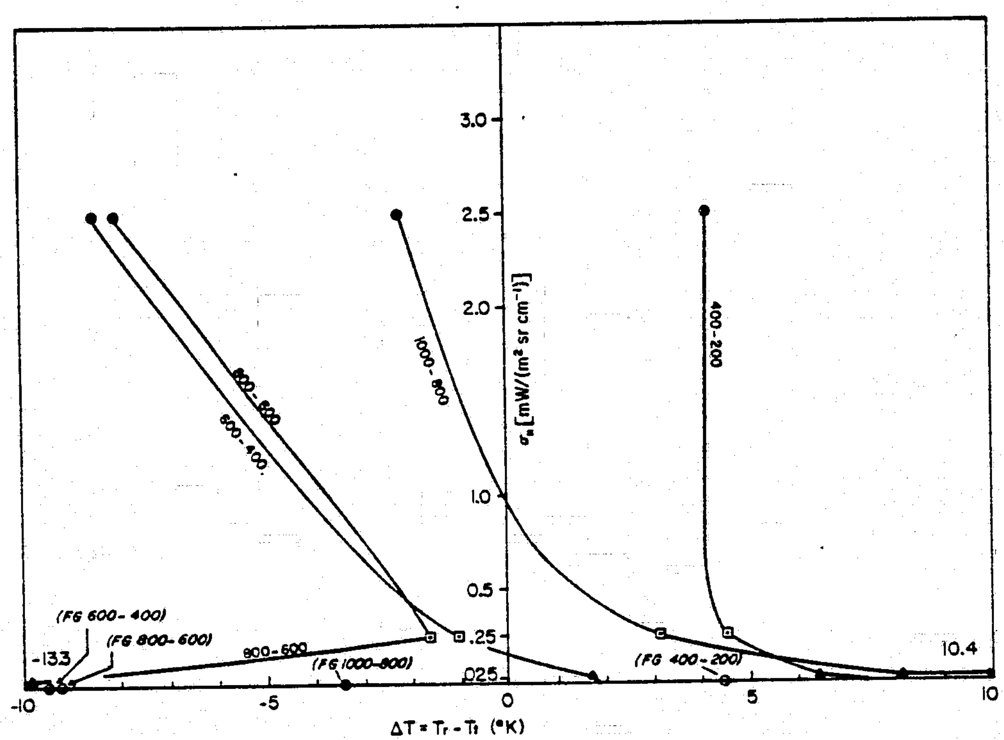

Fig. 2. Temperature errors, at Springfield, in the minimum-information retrievals as a function of the noise parameter σ_N. The temperature errors were averaged over the pressure intervals indicated on the curves. The first guess errors, for each layer, are indicated on the abscissa.

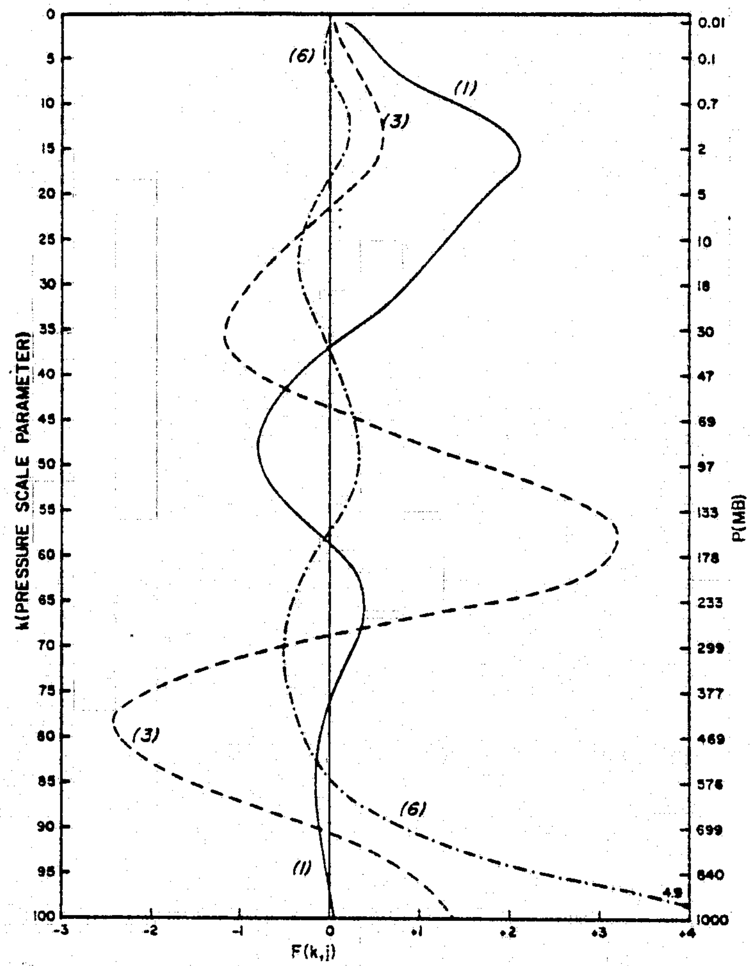

Fig. 3(a). Coefficients F(k,j) used in the minimum-information retrievals with Omaha temperatures as first guess. Only 3 of the six spectral intervals, j, are shown. Curve (1) is for channel (1), $\nu = 668.5\ cm^{-1}$; curve 3, $\nu = 695.3\ cm^{-1}$; curve 6, $\nu = 747.6\ cm^{-1}$. (ν = spectral frequency).

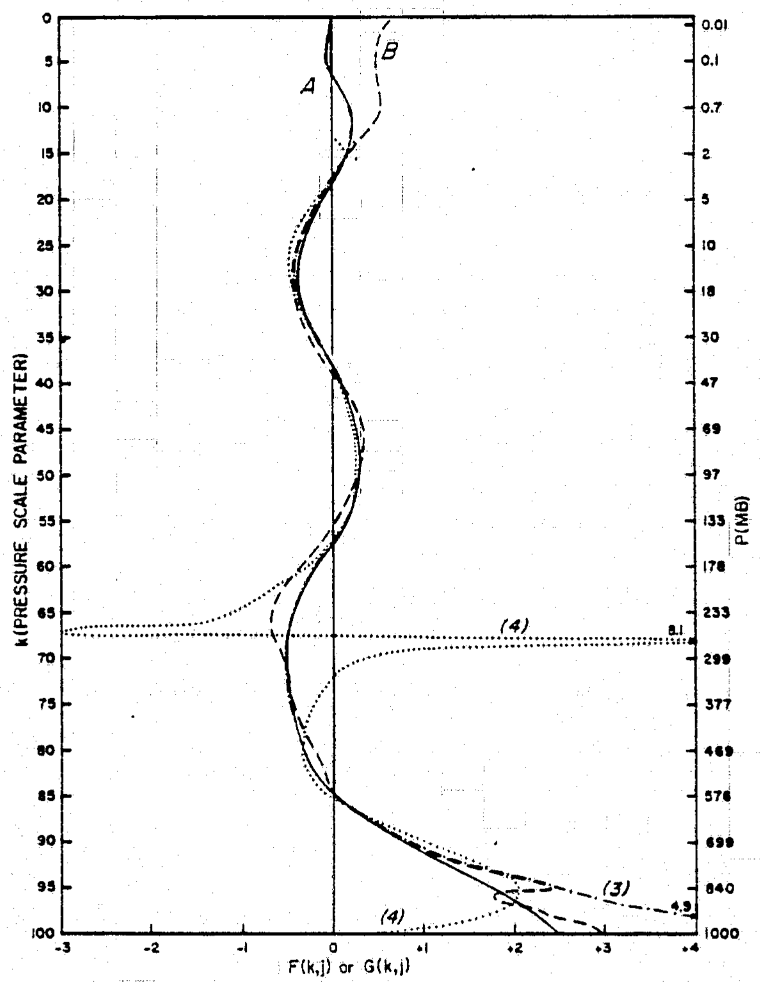

Fig. 3(b). Coefficients for channel 6, $\nu = 747.6\ cm^{-1}$. Curve (3) is for F(k,6) used in the minimum-information retrievals; this is the same as curve (6) in Fig. 3(a). Curve 4 is for G(k,6), used in adjustment method (2); curve (A) is for Method (3); and curve (B) is for Method (4). NOTE that all G(k,6) are substantially smaller than F(k,6), for k = 100, p = 1000 mbs.

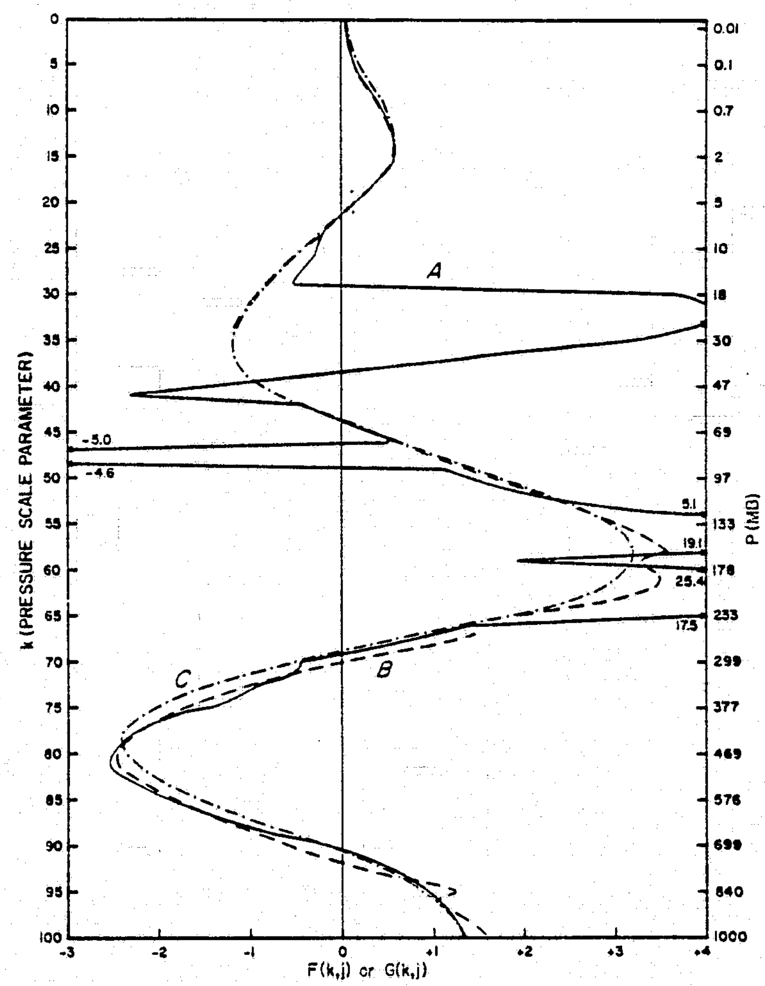

Fig. 3(c). Coefficients for channel 3, ν = 695.3 cm^{-1}. Curve (C) is for F(k,3) used in the minimum-information retrievals; this is the same as curve (3) in Fig. 3(a). Curve (A) is for G(k,3) used in adjustment method (3); and curve (B) is for Method (4).

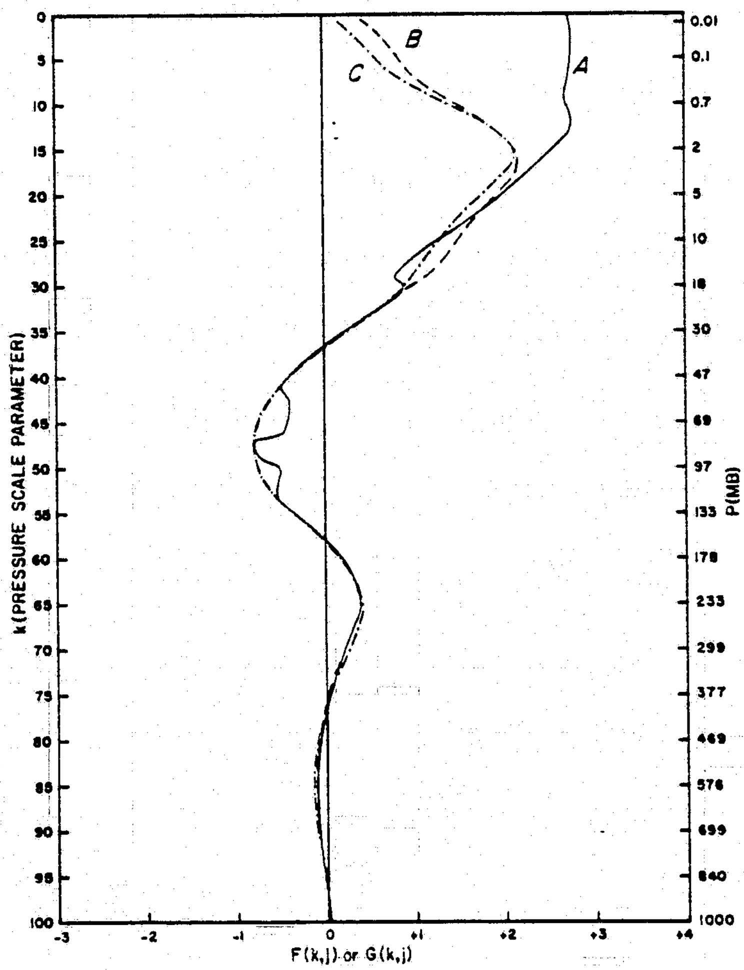

Fig. 3(d) Coefficients for channel 1, $\nu = 668.5\ cm^{-1}$. Curve (C) is for F(k,1) used in the minimum-information retrievals; this is the same as curve (1) in Fig. 3(a). Curve (A) is for G(k,1) for adjustment method (3); and curve (B) for Method (4).

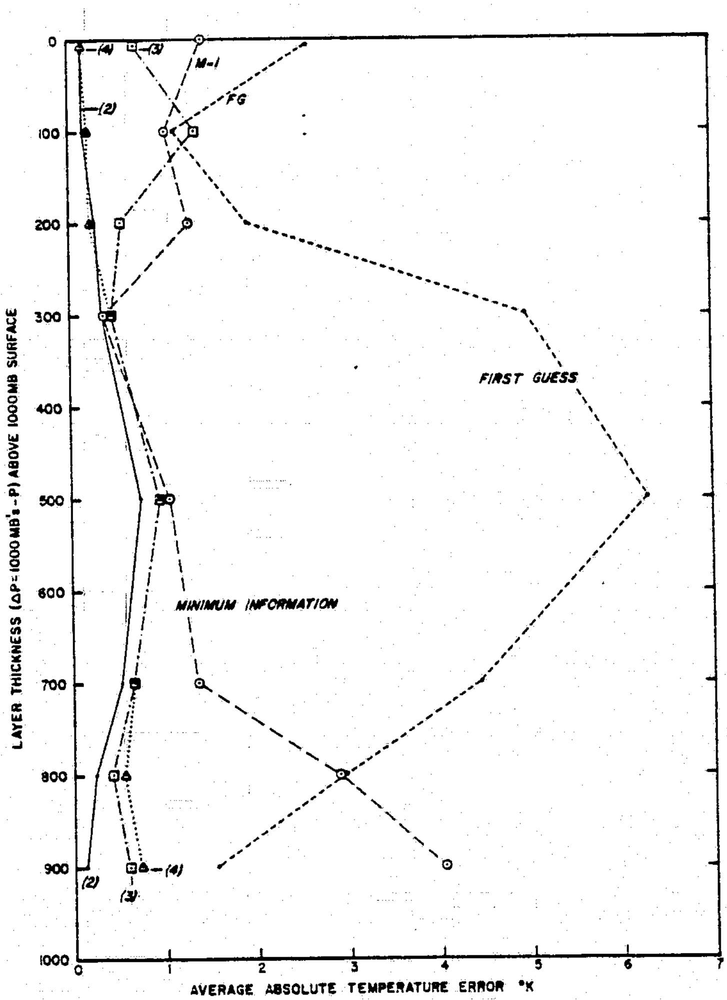

Fig. 4. The average absolute temperature errors for indicated layers. On the ordinate, "900" means the layer from 1000 to 900 mbs; "800" means 1000 to 800 mbs; "700" means 1000 to 700 mbs; etc. The curves labelled (2), (3), (4) refer to the "adjustment" retrieval methods (2), (3), (4). (see text).

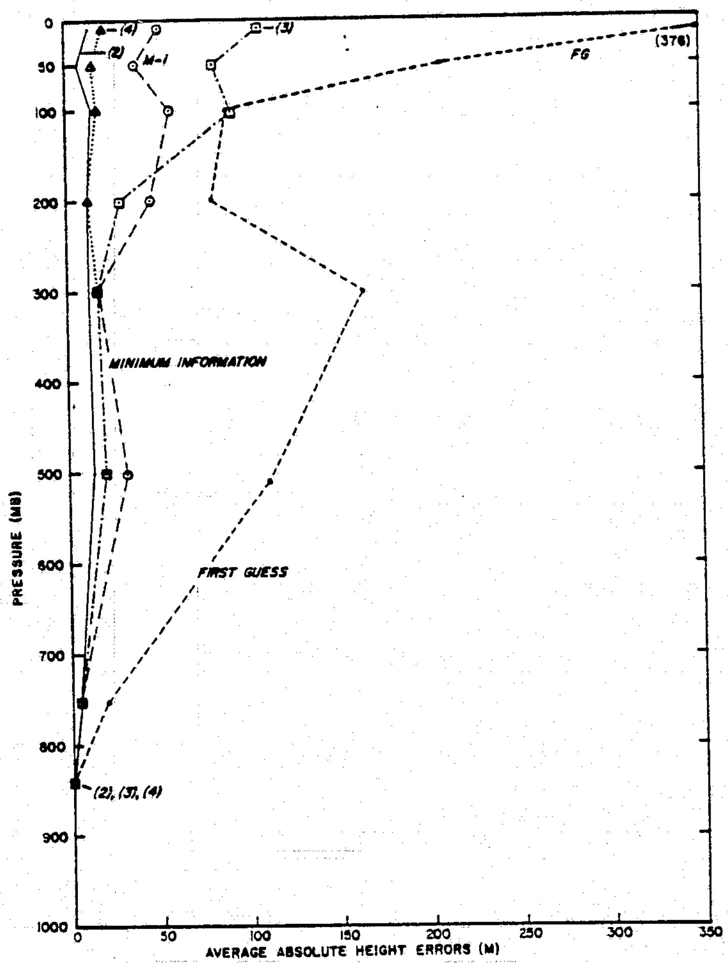

Fig. 5. Average absolute height errors at indicated pressure levels. The curves labelled (2), (3), (4) refer to the "adjustment" retrieval methods (2), (3), (4). (see text).

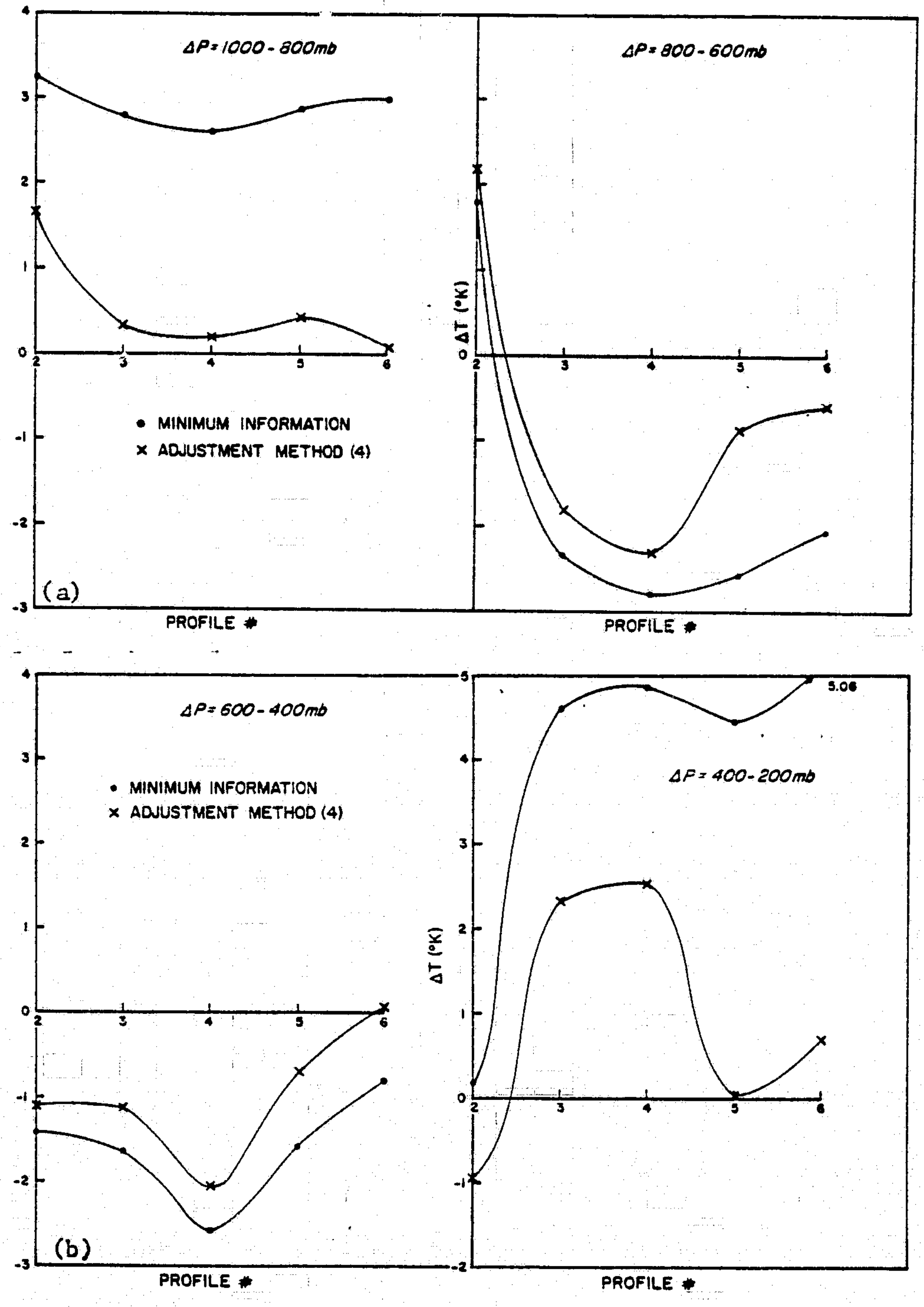

Fig. 6(a) and 6(b). Temperature errors, averaged over indicated pressure layers, at "stations" between Omaha and Springfield. Profile No. 2 means station at "Omaha +90 km"; No. 3 means "Omaha +180" km; etc.; No. 6 means "Omaha +450", or 90 km west of Springfield. Minimum-information method compared with adjustment method (4).

ABSTRACT

This paper presents a method for using satellite measurements to interpolate vertical temperature soundings between radiosonde stations. The calculations presented show that especially in the 1000-800 mbs layer, where linear methods of temperature retrieval usually contain large errors, the proposed method reduces the errors substantially.

The method finds a set of coefficients, which when multiplied by corresponding measured radiance quantities, yield zero temperature error at a radiosonde station. This derived set of coefficients is then applied to satellite radiance measurements at places between the radiosonde stations. The computations show, for example, that the average absolute error in the layer 1000-800 mbs is only 0.3K when the corresponding "minimum-information" method error was 2.9K. The method may be most applicable to measurements from geostationary satellites, but should also be applicable to measurements from polar orbiting satellites under certain conditions.

APPENDIX A

TEMPERATURE RETRIEVALS FROM SATELLITE RADIANCE MEASUREMENTS - AN EMPIRICAL METHOD*

by

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1. Introduction

Indirect soundings of atmospheric temperature from satellite radiance observations are now obtained operationally from polar orbiting satellites (McMillin, et al., 1973). In addition plans are going forward to mount a "sounding" instrument on a geostationary satellite (Shenk, 1976).

Two temperature retrieval methods have been used in operational practice. One is the so-called "minimum-information" method. The second is a regression method. Both are linear methods (Fritz et al., 1972, Fleming and Smith, 1972) and seek to find the "best" set of coefficients $F(k, j)$ in the following relationship:

$$\Delta B_r(k) = \sum_j F(k, j) \cdot \Delta R(j) \qquad (1)$$

$$B_r(k) = B_g(k) + \Delta B_r(k) \qquad (2)$$

$$\Delta R(j) = R_m(j) - R_g(j) \qquad (3)$$

In these equations

$B(k)$ = Planck function at the pressure level, k, at a reference frequency, usually taken at 700 cm^{-1}, when the 15 μm CO_2 band is used in the satellite measurements.

$R(j)$ is a radiance at the frequency, j.

The subscripts denote the following:

"g" = a guess (or initial estimate)

m = the measured value

r = the retrieved value.

Because $B(k)$ depends only on the temperature, $T(k)$, it is easy to compute $T(k)$ from the inverse of the Planck function, once $B(k)$ is known.

Unfortunately, the derived or retrieved temperatures often contain fairly large errors; in actual practice the RMS errors when compared with radiosondes are usually about 3K in the layer from 1000 to 800 mbs and also near the 200 mb level (Fritz, 1974; Weinreb and Fleming, 1974; Werbowetski, 1975). Even with idealized, simulated "data", the average absolute error is usually about 3K (Fleming and Smith, 1972). In part these errors in temperature retrievals are related to the shape of the vertical temperature profile (Fritz, 1969); the retrievals are not able to reproduce discontinuities well, and such discontinuities occur at the ground and at the tropopause.

In this paper, a method is proposed which can improve the temperature retrieval accuracy especially in the lower atmosphere and probably near the tropopause also. The results will be compared with computations derived from the minimum-information method.

2. The minimum-information method

In all temperature retrieval methods, satellite radiances are measured at a set of frequencies. We shall use the six CO_2 15 μm frequencies observed by the VTPR (Vertical Temperature Profile Radiometer) on NOAA satellites (McMillin et al., 1973).

TABLE 1

Frequencies of channels used (cm^{-1})

Channel No.	1	2	3	4	5	6
Frequency	668.5	677.9	695.3	708.6	725.5	747.6

In the minimum-information method the values of F(k, j) in Eq. 1 are given by (Fritz, et al., 1972, Fleming and Smith, 1972):

$$F(k, j) = \sigma_T^2 A^T (A\sigma_T^2 A^T + \sigma_N^2 I)^{-1} \tag{4}$$

where -1 denotes the inverse matrix

A = the matrix of $\frac{d\tau}{dx}(k, j)$

A^T = the transpose of A

σ_T^2 = the co-variance of temperature between levels k in an ensemble of temperature profiles, but assumed constant.

σ_N^2 = the variance of noise in the observations; instrument noise assumed.

$\tau(k, j)$ = the atmospheric transmittance from the level, k, to the top of the atmosphere, at the spectral frequency, j.

x = a height parameter, taken as proportional to $p^{2/7}$.

In the minimum-information method, σ_T^2 is taken as constant although in fact it varies with height. For σ_N^2, the instrumental noise is usually assumed, although other factors, such as clouds, introduce "noise" into the observations. In this study $\sigma_T^2 = 100$ was assumed, and $\sigma_N = 0.50$ for channel 1 and $\sigma_N = 0.25$ for the five remaining channels. [The transmittances, and temperature corrections for the transmittance were kindly supplied in a computer program by Dr. M. P. Weinreb (NESS/NOAA)]. The program contains 100 levels for k, and six spectral intervals for j. The inverse matrix in Eq. (4) is so complex that, even for well behaved functions it is not possible to predict the values of F(k, j) in advance. In addition, the values of F(k, j) are highly sensitive to values of σ_N and σ_T selected.

It is likely therefore that near any particular place and time, the set of F(k, j) may not be the "best". Furthermore, because of the

assumptions adopted in the minimum information method, the set of $F(k, j)$ may not even be the "best" set for an ensemble.

Even if $\Delta R(j) = 0$ in Eq. (1), the retrieval $B_r(k)$ will in general not agree with the true value, $B_t(k)$, at a level k, although $B_r(k)$ may oscillate about the true values in some unpredictable manner. In particular, as stated earlier, large deviations from the true values appear in the lower atmosphere and near the tropopause.

It therefore, seemed reasonable to modify the set of $F(k, j)$ in order to force $B_r(k)$ to equal the true values, $B_t(k)$, for at least one sounding. After the new set of coefficients, $G(k, j)$ had been selected, giving errorless retrievals for a known temperature profile at a radiosonde station, the set of $G(k, j)$ could be used to interpolate between radiosonde stations, or extrapolate in time between the times of radiosonde observations. This interpolation and extrapolation capability might be especially useful when continual radiance observations become available from geostationary satellites. The interpolation capability, between radiosonde sounding stations, might also be useful for radiances observed from polar orbiting satellites, since the field of view of the satellite radiometers is often much smaller than the distance between radiosonde stations. However, such interpolation and extrapolation capabilities would be most useful in rapidly changing, small scale situations, provided the temperature changes were large enough; for this reason the application to the continual observations from geostationary satellites might be more promising. Unfortunately such situations are often accompanied by complicated cloud fields, which may introduce errors into the "clear-column" radiances

required in most retrieval methods. Nevertheless, in this paper, it will be assumed that accurate "clear-column" radiances are available.

3. Adjusting the coefficients; the adjustment method

Let us find a set of coefficients, such that

$$\Delta B'_r(k) = \Delta B_t(k) = \sum_j G(k, j)\cdot\Delta R(j) \tag{5}$$

$$B'_r(k) = B_t(k) = B_g(k) + \Delta B_t(k) \tag{6}$$

The subscript, t, denotes the true value of the quantity.

If we divide Eq. (6) by Eq. (2),

$$\Delta B_t(k)/\Delta B_r(k) = [B_t(k) - B_g(k)]/[B_r(k) - B_g(k)] = C(k) \tag{7}$$

The quantity C(k) will be a constant for a particular level, after the minimum-information retrieval determines the value of $B_r(k)$. Substituting for $\Delta B_r(k)$ from Eq. (1), we obtain

$$\Delta B_t(k) = C(k)\cdot\Delta B_r(k) = \sum_j C(k)\cdot F(k, j)\cdot\Delta R(j) \tag{8}$$

$$= \sum G(k, j)\cdot\Delta R(j) \tag{9}$$

$$G(k, j) = C(k)\cdot F(k, j) \tag{10}$$

4. Test of the Adjustment Methods

To test the proposed method, several numerical tests were made. All the tests improved the minimum-information retrievals, especially in the lower atmosphere. One expects the satellite radiances to yield the most significant results where large temperature variations occur. Therefore, a tornado producing situation, with large horizontal temperature gradient was selected. Danielsen (1975, see p. 180) shows a vertical cross-section

of potential temperature which contained a marked gradient between Omaha, Nebraska and Springfield, Illinois. These stations are about 550 km apart. From Danielsen's cross section, vertical temperature profiles were computed at five additional points located at every 90 km between Omaha and Springfield. Thus seven soundings were available, including Omaha and Springfield. Above the top (about 160 mbs) of Danielsen's diagram, an arbitrary climatological temperature sounding, typical of the latitude and time (April), was added up to the 0.01 mb level (about 80 km). (This climatological temperature add-on was also supplied by Dr. Weinreb). For each of the seven locations the radiance was computed from the temperature profiles from the radiative transfer equation,

$$R(j) = \sum_k B(k, j) \cdot \Delta\tau(k, j) + B_s(j)\tau_s(j) + N(j) \qquad (11)$$

where $B_s(j)$ is the Planck function corresponding to the surface temperature and $\tau_s(j)$ is the transmittance through the entire atmosphere at the frequency, j. The $B(k, j)$ are computed from the temperatures, $T(k)$, from the Planck function formula. The quantity N is a random number added to represent instrumental noise. This was selected from a sub-routine which generated random numbers with a mean of zero and a standard deviation of 0.5 for Channel 1, and 0.25 for the other channels. The experiment was also run with $N = 0$. The results were essentially the same.

The radiances, $R(j)$, in Eq. (11) were normalized to radiances at 700 cm^{-1} so that in the minimum-information retrieval, quantities involving $B(k)$ in Eq. (1) have all been scaled to 700 cm^{-1}; the temperatures can then be readily computed from the Planck function $B(k,700)$ which are also the B's in Eq.1.

With these simulated "measured" radiances, $R_m(j)$, from Eq.(11), the minimum-information retrievals were obtained as follows:

The Omaha sounding was used as the "first-guess" or initial estimate. This supplied values of $B_g(k)$ and of $R_g(j)$. With the aid of the Omaha temperatures, and the τ's, a set of $F(k,j)$ was computed from Eq.(4). With these values and the $R_m(j)$ for Springfield $B_r(k)$ was obtained from Eqs.(1) and (2); these are the retrieved values for Springfield.

Using the Springfield temperatures as the truth, we compute $C(k)$ from Eq.(7); and from $C(k)$ and $F(k,j)$ we compute

$G(k,j)$ from Eq.(10).

These values of $G(k,j)$, when used with the Springfield radiances and Omaha temperatures as the first guess, yield a retrieval with zero error at all pressure levels at Springfield.

Now these same values of $G(k,j)$ and the same Omaha temperature sounding as first guess were used to obtain retrievals at the five locations <u>between</u> Omaha and Springfield. For comparison the retrievals were also obtained at those five locations with the minimum-information method, also using Omaha as the first guess.

The results* are shown in Table 2. The column labelled "adjustment method" is the method involving $G(k,j)$.

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*The results shown here were not obtained by iteration; when the minimum-information solutions were obtained by iterations, the results were often poorer.

TABLE 2

Average Absolute Temperature Error; Deviation from True Temperature (^{o}K)

	First Guess	Minimum-Information	Adjustment Method
Δp (layer)			
1000-800	3.0	2.9	0.3
800-600	7.4	2.3	1.2
600-400	7.1	1.6	1.0
400-200	4.0	3.8	1.2
200-5	4.6	0.1	0.2

Table 2 shows that the average absolute error is smaller for the adjustment method than for the minimum-information method, except for the 200-5 mb layer. In the lowest layer, 1000-800 mbs, the value 2.9K is similar to the errors found both operationally and in other theoretical studies. By contrast, the average absolute error by the adjustment method was only 0.3K. In the lowest layer, the minimum-information method shows essentially no improvement over the first guess error, but the adjustment method error is substantially smaller than the first guess error. In the middle atmosphere, 600-400 mb layer, where the minimum-information method usually shows its best results, the error is 1.6K, a substantial improvement over the first-guess error of 7.1K. But even here, the adjustment method error was smaller, namely about 1.0K.

It is also interesting to examine the height errors for specific pressure levels. The height levels were computed by assuming that the height of the 850 mb surface was 1330 m; heights at other pressure levels were computed from this height and the temperature profiles. The heights therefore serve as a comparison of the average temperatures from 850 mb to the height of the particular pressure surface. Table 3 shows the height

errors at all the "stations", for the 510 mb pressure level (one of the "k" levels was at 510 mb). In all cases except the "Omaha + 90 km" station, the height errors were smaller for the "adjustment" method. However, the height gradients, illustrated by $\Delta E(z)$ in Table 3, were fairly similar for the two methods of retrieval. It would appear therefore that if both satellite data and radiosonde data were used without adjustment to determine the height field, there would be a marked discontinuity near some radiosonde stations (e.g., Springfield) when compared with minimum-information retrievals. With the adjustment method however, the height field at nearly every station has been moved up to more nearly agree with the true heights. Of course this adjustment is forced to be exact at Springfield so that both satellite data and radiosonde data agree there.

Finally, it should be pointed out, that a linear interpolation of the height field between Omaha and Springfield contains even larger height errors than those shown in Table 3; in this example, the variation of height between Omaha and Springfield was non-linear, and the satellite "data" yielded heights closer to the truth than linear interpolation of the height field did.

TABLE 3

Height Errors (m) for the 509 mb Pressure Surface

Station	Omaha		+90 km		+180		+270		+360		+450		Springfield
First Guess (Deviation from True) (Omaha = First Guess)	0		-29		-115		-135		-139		-141		-142
(Minimum-Information)	0		14		-35		-42		-36		-28		-28
$\Delta E(z)$		+14		-49		-7		+6		+8		0	
Adjustment	0		23		-16		-21		-12		-1		0
$\Delta E(z)$		+23		-39		-5		+9		+11		+1	

$\Delta E(z)$ = the error in difference of heights between adjacent stations

5. Discussion and Conclusion

We have demonstrated that if accurate radiances can be obtained from satellite measurements, then it is better to adjust the minimum-information coefficients, F(k,j), so that at least one satellite temperature retrieval sounding agrees exactly with its corresponding radiosonde temperature sounding, than to use the minimum-information retrievals themselves. This would apparently be especially valuable in the lower atmospheric layers where large temperature errors appear both in operational results and in other theoretical studies. For the two classes of cases we studied, the Gate ship soundings (not reported here) and the Omaha-Springfield tornado situation, the coefficients F(k,j) were too large by a factor of 3 or more near the 1000 mb level. This raises the question as to whether the assumptions, which enter the minimum-information method, always give too much weight to the coefficients in the lower layers.

However, the method proposed here, the Adjustment Method, has some problems too. For example, the factors C(k) in Eq.(7) may become unstable if $B_r(k) \approx B_g(k)$. Substantial oscillations of C(k) were encountered in this study too. But these were confined to narrow layers, and always oscillated in sign in these layers. This sign variation, of course, reduces the oscillation to small amplitude when temperature averages over layers are calculated. If it is necessary to reduce the temperature error at every level, k, then the G(k,j) can be averaged before the temperatures are calculated. This will no longer produce zero error at every level, k, at the adjustment station (Springfield in this study), but the error will still be small, and the error over layers will still be nearly zero, because of the linearity of the operations. Alternatively, additional methods may be developed to compute

$G(k,j)$ such as limiting $\sum_j G(k,j)$ to some constant value. Such methods are being investigated further.

The Adjustment Method discussed here suggests application to geo-stationary satellite radiances. For in that case frequent observations with relatively high spatial resolution will become available. Therefore observations would be available to study phenomena which are changing rapidly between the 12 hour radiosonde interval and also phenomena which are smaller in size than the distance between radiosonde stations. However, clouds and water vapor will introduce errors in the "clear-column" radiances in these small time and space scale phenomena. The reduction of such radiance errors will present a challenging problem.

Furthermore, it may also be possible to improve the temperature soundings from polar orbiting satellites with the proposed methods. The references already cited show that the largest errors occur near the earth's surface and also near the tropopause. In the tropics where the shape of the vertical temperature profile does not change much with time or space it might be desirable to use the adjustment method. For example, we might be able to take the Barbados sounding as a first guess, and retrieve the Dakar temperature profile with the minimum-information method. Then adjust the coefficients $F(k,j)$ so that the Dakar sounding is matched with no error. Finally, use the new coefficients, $G(k,j)$, to retrieve temperatures for Atlantic Ocean areas in between, and also into the Caribbean Sea area. Verification can be checked with the other Caribbean Sea area radiosonde stations and with the island stations near Dakar.

Care must of course be taken that the radiosonde pair selected are themselves on the same scale; for apparently radiosondes from different countries may not all be on the same scale. At first, it might be better to test with the Gate or Bomex ship data, to avoid discrepancies between the low level island temperatures and temperatures over the sea. Such procedures may improve the operational satellite temperature retrievals both near the surface and near the tropopause.

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APPENDIX B

Methods of adjusting F(k,j) to G(k,j) (see p. 4)

so that $T_t(k) - T_r(k) = 0$ at Springfield, Illinois

Method (1) (see Appendix A)

Change only $F(k,j_{max})$

Given: $B_r(k)$ = minimum-information retrieval at Springfield based on

$B_g(k)$ = first-guess Planck functions for

Omaha, Nebraska, the first-guess station, and

$$\Delta B_r(k) = \sum_j F(k,j) \cdot \Delta R(j)$$

j_{max} = the frequency for which $|F(k,j)|$ has its maximum value at a given k.

For the minimum-information retrievals

$$B_r(k) = B_g(k) + \Delta B_r(k) \tag{1}$$

$$\Delta B_r(k) = \sum_j F(k,j) \cdot \Delta R(j) \tag{2}$$

Let the true value of B be given by

$$B_t(k) = B_g + \Delta B_t(k) \tag{3}$$

subscript, t, means true value.

Let $$\Delta B_t(k) = \sum_j G(k,j) \cdot \Delta R(j) \tag{4}$$

$$\Delta B_t(k) - \Delta B_r(k) = [B_t(k) - B_g(k)] - [B_r(k) - B_g(k)]$$

$$= B_t(k) - B_r(k) \tag{5}$$

Therefore, from eqs. 2, 4, and 5

$$\sum_j G(k,j) \cdot \Delta R(j) - \sum_j F(k,j) \cdot \Delta R(j) = B_t(k) - B_r(k)$$

or

$$\Sigma[G(k,j) - F(k,j)] \cdot \Delta R(j) = B_t(k) - B_r(k) \tag{6}$$

Assume that $G(k,j) = F(k,j)$ except for that value of j for which $|F(k,j)|$ has a maximum value; this maximum value is defined separately for each value of k. Therefore, from eq. 6,

$$[G(k,j_{max}) - F(k,j_{max})]\cdot\Delta R(j_{max}) = B_t(k) - B_r(k)$$

or

$$G(k,j_{max}) = \frac{B_t(k) - B_r(k)}{\Delta R(j_{max})} + F(k,j_{max})$$

$$= C(k) + F(k,j_{max})$$

Method (2)

Change all F(k,j)

As in Method (1)

$$\Delta B_r(k) = B_r(k) - B_g(k) = \sum_j F(k,j)\cdot\Delta R(j) \qquad (1)$$

$$\Delta B_t(k) = B_t(k) - B_g(k) = \sum_j G(k,j)\cdot\Delta R(j) \qquad (2)$$

Dividing eq. (2) by eq. (1)

$$\Delta B_t = [\frac{B_t(k) - B_g(k)}{B_r(k) - B_g(k)}]\Delta B_r(k) \qquad (3)$$

$$= C(k)\cdot B_r(k) \qquad (4)$$

once $B_r(k)$ is obtained from the minimum-information retrieval.

From eqs. 1-4

$$\sum_j G(k,j)\cdot\Delta R(j) = C(k)\sum_j F(k,j)\cdot\Delta R(j)$$

$$= \sum_j C(k)\cdot F(k,j)\cdot\Delta R(j)$$

Therefore

$$G(k,j) = C(k)\cdot F(k,j)$$

is a relationship which will force $T_r = T_t$ at Springfield, Illinois if the temperature profile at Omaha, Nebraska is the first-guess.

Method 3

$\Sigma G(k,j) = 1$

and

Change the two values of F(k,j) for which the absolute values of F(k,j) are the largest.

As in Methods (1) and (2)

$$\Delta B_r = \sum_j F(k,j)\cdot\Delta R(j) \quad (1)$$

$$\Delta B_t = \sum_j G(k,j)\cdot\Delta R(j) \quad (2)$$

Let

$$\sum_j G(k,j) = 1 \quad (3)$$

and adjust only $|F(k,j_{max})|$ and $|F(k,j_{max-1})|$; j_{max} is the frequency for which $|F(k,j)|$ is a maximum; j_{max-1} is the frequency for which $|F(k,j)|$ has the second largest value at the level, k.

For all other values of j

$$G(k,j) = F(k,j) \quad (4)$$

Therefore

$$\Delta B_r(k) = F(k,j_{max})\cdot\Delta R(j_{max}) + F(k,j_{max-1})\cdot\Delta R(j_{max-1}) + \sum_j^4 F(k,j)\cdot\Delta R(j) \quad (5)$$

$$\Delta B_t(k) = G(k,j_{max})\cdot\Delta R(j_{max}) + G(k,j_{max-1})\cdot\Delta R(j_{max-1}) + \sum_j^4 F(k,j)\cdot\Delta R(j) \quad (6)$$

and from eq. (3)

$$G(k,j_{max}) + G(k,j_{max-1}) + \sum_j^4 F(k,j) = 1 \qquad (7)$$

$\sum_j^4$ = sum over the four values for which $j \neq j_{max}$
$j \neq j_{max-1}$

Eqs. (6) and (7) constitute two equations in the two unknowns, $G(k,j_{max})$ and $G(k,j_{max-1})$.

Multiply eq. (7) by $\Delta R(j_{max-1})$ and subtract from eq. (6).

Then,

$$\Delta B_t(k) - \Delta R(j_{max-1}) = G(k,j_{max})\cdot\Delta R(j_{max}) - G(k,j_{max})\cdot\Delta R(j_{max-1})$$
$$+ \sum_j^4 F(k,j)\cdot\Delta R(j) - [\sum_j^4 F(k,j)]\cdot\Delta R(j_{max-1})$$

$$G(k,j_{max}) = \{\Delta B_t(k) - \Delta R(j_{max-1}) - \sum_j^4 F(k,j)\cdot\Delta R(j)$$
$$+ [\sum_j^4 F(k,j)]\cdot\Delta R(j_{max-1})\}/\{\Delta R(j_{max}) - \Delta R(j_{max-1})\} \qquad (8)$$

Once $G(k,j_{max})$ is computed from eq. (8), we compute

$G(k,j_{max-1})$ from eq. (7)

$$G(k,j_{max-1}) = 1 - G(k,j_{max}) - \sum_1^4 F(k,j)$$

<u>Method 4</u>

In Method 3 the denominator in eq. 8 may become small when

$$\Delta R(j_{max}) \simeq \Delta R(j_{max-1}).$$

When this happens the coefficient $G(k,j_{max})$ may become rather large, and the retrieval temperature errors may become large when the coefficients are applied to independent satellite "measurements".

To remedy this defect a procedure similar to the one for Method 3 can be used. But now select $R(j_{max})$ and in addition one other $R(j)$ [not necessarily $R(j_{max-1})$]. Select the second $R(j)$ such that

$$|\Delta R(j_{max}) - \Delta R(j)| \text{ is a maximum.}$$

The procedure is as follows:

Find $F(k,j_{max})$; this defines j_{max} and therefore $\Delta R(j_{max})$. Now test each $\Delta R(j)$ to see which one makes

$$|\Delta R(j_{max}) - \Delta R(j)| \text{ a maximum.}$$

For six measured channels, the newly selected "j" could take on any one of five values. After the second "j" has been selected, designated j', proceed as in Method 3 except that j' replaces j_{max-1}. Then

$$G(k,j_{max}) = \{\Delta B_t(k) - \Delta R(j') - \sum_j^4 F(k,j)\cdot\Delta R(j) + [\sum_j^4 F(k,j)]\cdot\Delta R(j')\}/\{\Delta R(j_{max}) - \Delta R(j')\};\ j \neq j_{max} \neq j'$$